Pergamon

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Energy 28 (2003) 557–574

ENERGY

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Application of thermoeconomics to the allocation of environmental loads in the life cycle assessment of cogeneration plants

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Received 9 March 2001

Abstract

One of the most common problems arising from the application of life cycle assessment is the allocation of environmental loads in processes yielding several useful products. This is the case for cogeneration plants, and in general, for any energy plant producing more than one useful energy flow. Since traditional solutions to the problem are unsatisfactory, two new approaches for this kind of allocation are presented in this report, both of them based on thermoeconomics. In the first one, allocation is based on the exergetic cost of the products, so that the formation process of energy flows is taken into account. The second one, which has been called 'method of the exergoenvironmental costs', is a refined version of the first solution. It differs as each environmental vector is incorporated in the balance at the exact point in the plant where it comes into play. These methods are a generalisation of thermoeconomics, extending the applicability of its propositions to the allocation of environmental burdens. A comparison between the different allocation methods and a discussion pertaining to their suitability are made.

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1. Life cycle assessment and the allocation of environmental loads

Life cycle assessment (LCA) is a tool for assessing the environmental impacts of a product throughout its entire life, from raw materials extraction to production, use and disposal. Impacts to be considered include resource depletion, human health and ecological health. The most

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doi:10.1016/S0360-5442(02)00156-1

accepted LCA methodology comprises four steps: (a) goal definition and scoping, (b) inventory analysis, (c) impact assessment, and (d) improvement analysis.

The second step, named life cycle inventory, consists of the identification and quantification of all the emissions (outputs) and raw materials consumption (inputs) during a product's entire life cycle. The result of this inventory is a long list of emissions and raw materials, which are called 'environmental loads'. In the impact assessment, these loads are sorted by their effect (classification), the degree to which they contribute to the effect being expressed by a weighting factor (characterisation). How the effects should be weighted relative to each other is addressed in the last phase (valuation). Although the development of the LCA methodology has progressed significantly since 1990, there are still some outstanding issues. Further information about LCA can be found in references [1–3].

One of the most important and frequent methodological problems to be tackled when carrying out the life cycle inventory is the allocation of environmental loads in processes in which there are several useful products (co-products), as illustrated in Fig. 1. The question to be answered is: In a process in which a number of products are obtained, what loads or what part of these loads must be assigned to each product? Different solutions were proposed in a workshop on allocation in LCA organised by the Centre of Environmental Science of Leiden University in 1994 [4]. The problem can be found, for example, in a refinery, where many products are obtained and many environmental impacts take place.

Cogeneration constitutes a clear example. In a cogeneration plant's life cycle, a number of environmental loads arise, which are identified and quantified in the inventory phase, and the plant generates several useful energy flows (electrical power, steam at different pressures, heating water, refrigeration, etc.). In this report we seek to answer the question of how to distribute the environmental loads produced in a cogeneration plant's life cycle between the different products. It is necessary to develop a systematic approach that reflects, as accurately as possible, the causalities within the plants. This will be accomplished by the application of thermoeconomics.

The proposed methods will be applicable to any process in which a number of energy flows are obtained. The report, therefore, gives a solution to a specific problem of the LCA methodology and broadens the application of thermoeconomics to environmental issues.

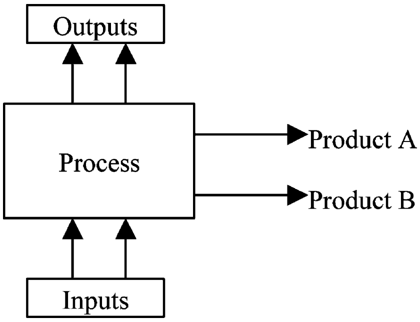

Fig. 1. Multi-output process.

2. Description of the cogeneration plant and life cycle inventory

In order to compare the allocation methods, a combined cycle located in a paper mill is taken as an example. In this plant, a gas turbine (GT) and a steam turbine (ST) generate electrical power, and steam at various pressures is introduced to the process.

The GT's net power output is 10,140 kW and it admits steam injection at 20 bar into the combustion chamber. The GT's flue gases are ducted to a heat recovery boiler (HRB) provided with an auxiliary firing system, in which steam at two pressures and superheated water are produced. The high-pressure (HP) steam is generated at 30 bar and 420 °C and expands through a back-pressure ST. A small amount of this steam is throttled in an expansion valve down to 20 bar and is mixed with cold water before being injected into the GT's combustion chamber. Low-pressure (LP) steam is generated at 4 bar and 180 °C and is carried to the process. Superheated water enters the boiler at 71 °C and leaves it at 102 °C, being used to preheat make-up water for both steam circuits. The condensate return rate is 80%; and this condensate, whose temperature is approximately 110 °C, is mixed with make-up water (preheated up to 88 °C) so that it enters the boiler at 105 °C in both circuits.

There is also a black liquor boiler of 45 t/h. This boiler provides HP steam (30 bar), which is mixed with that coming from the HRB to feed the ST. This turbine, whose power output is 5 MW, has an isoentropic efficiency of 83% and a back-pressure of 4 bar, part of the steam being extracted at 12 bar. Fig. 2 depicts a scheme of the cogeneration plant. The plant's components and energy flows have been numbered in the way they will be considered in the theory presented later.

The black liquor boiler causes awkward problems in the analysis to be developed due to the fact that the black liquor's life cycle and the paper production's life cycle are linked, thereby

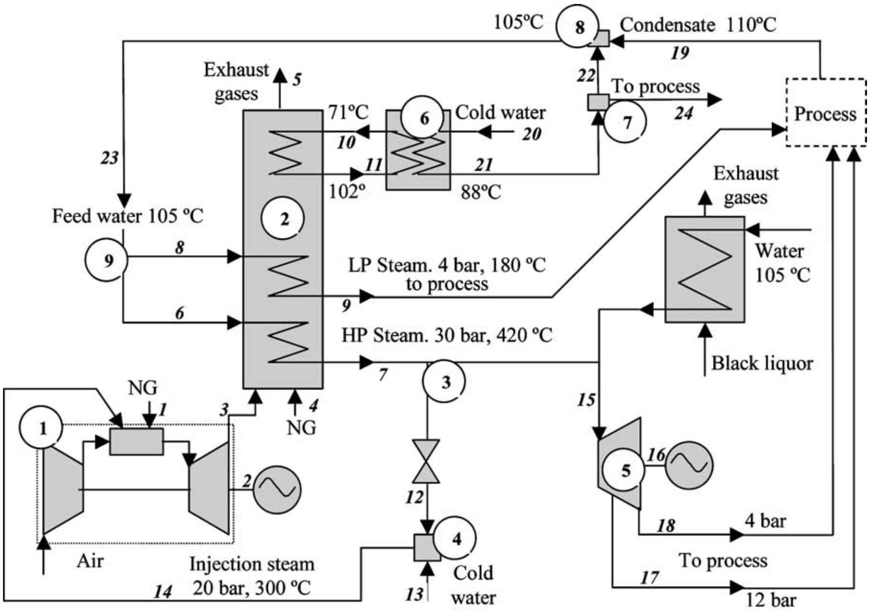

Fig. 2. Cogeneration plant in a paper mill. The numbers in circles correspond to the subsystems and the numbers in italics to the flows.

raising a different allocation problem. For this reason this boiler has been left aside, and only steam coming from the HRB is assumed to expand through the ST. Such an assumption does not affect our analysis at all.

In the life cycle inventory, the environmental burdens associated with the manufacturing, maintenance and decommissioning of the equipment must be taken into account, as well as the extraction, preparation and transport of natural gas (the so-called ‘pre-combustion’ process) and, of course, the emissions during the plant operation. The impact analysis carried out by the authors reveals that the relative weight of the impacts associated with the plant’s infrastructure is under 5% of the total [5], and thereby they have been removed from the analysis, following the mainstream practice [3]. However, natural gas pre-combustion life cycle is of major relevance, exceeding 25% of the total impact. Gas pre-combustion inventory data were derived from the inventory of energy systems developed by the Swiss Federal Institute of Technology in Zürich (ETH), which is a widely used reference [6]. As this inventory includes more than 500 different emissions, it is not possible to show it in detail. Only the most important environmental burdens are displayed in Table 1, referred to 1 TJ (terajoule) of gas (LHV lower heating value).

Evidently, the most important contribution is that of air-borne emissions during plant operation. Such emissions originate from combustion in the GT and the HRB’s duct burner. Emissions per burnt gas unit are very different in these two components, to such an extent that even part of the CO and NO_X produced in the GT are destroyed in the HRB. This fact accounts for the negative figures in the right column of Table 2, in which emissions per TJ of burnt gas (LHV) are displayed for both devices. The data were obtained from technical literature and manufacturers.

These emissions, together with those released during the gas pre-combustion, make up the life cycle inventory. In the analysed plant there are several useful products, namely electrical power generated by the GT and the ST, LP steam, back-pressure steam, extracted steam and superheated water. The problem to be solved is thus how to allocate the environmental loads between these products. Although it is beyond the scope of this paper, the ultimate goal would be the allocation

Table 1
Most relevant emissions in natural gas pre-combustion, referred to the LHV

Emission	NG (kg/TJ)
CO_2	12,505
CO	17.55
NO_X (as NO_2)	25.74
CH_4	236.45
SO_2	11.17
Particles	2.7
Heavy metals	0.0419[a]
Ethane	20.90
Propane	5.49
Butane	1.74
Other NMVOC[b]	14.07

[a] Pb equivalent.

[b] Non-methane volatile organic compounds.

Table 2
Emissions from natural gas combustion in the GT and the post-combustion burner, referred to the LHV

Emission	NG GT (kg/TJ)	NG post (kg/TJ)
CO_2	59,100	59,100
CO	111.38	−232.22
NO_X (as NO_2)	167.08	−456.93
CH_4	17.13	8.728
SO_2	0.52	0.52
Particles	4.2	0.2
Hg	0.000055	0.000055
Ethane	0.324	0.324
Propane	4.30	0.0748
Butane	9.32	0.0249
Pentane	13.53	0.0125
Formaldehyde	8.45	0
Acetaldehyde	0.0084	0
Acetic acid	3.38	0
Propionic acid	1.69	0
PAH[a]	0.01	0
Benzo(a)pyrene	0.00001	0

[a] Polycyclic aromatic hydrocarbons.

of those loads to the market products of the factory where the cogeneration plant is located. Excess electricity may be one of these products.

3. Traditional solutions to the allocation problem

According to Finnveden [7], the various allocation principles may be divided into five groups:

- Allocation based on natural causality. If there are natural identifiable causalities for environmental loads, allocation must be based on these.
- Allocation based on some physical parameter. Examples of physical quantities are: mass, volume, energy, exergy, number of moles, etc.
- Allocation based on social causes of the process. The justification for a process is that it produces value. This value may or may not be measurable in economic terms.
- Allocation based on an arbitrary number. This criterion should only be used in case there is no other possibility.
- Extension of system boundaries, avoiding the allocation problem.

In principle, it does not seem feasible to establish physical causation between the emissions and the different products of a cogeneration plant (first criterion). The common solution (second criterion) is to regard the plant as a black box and to make a distribution of the total identified loads according to a physical parameter of the products. This allocation procedure may look arbitrary to some extent, but for any allocation problem this parameter must be chosen in such a way that it describes the products and the possible process causation in the most appropriate manner. In the case of an energy conversion plant, the energy of the products is a very poor parameter, exergy being far more suitable. Allocation based on energy would penalise electrical power much more than other energy flows of lower quality. Exergy takes into account the quality of the different kinds of energy and expresses their actual equivalence. A number of authors back the use of the exergy of products as the allocation guiding principle [6,8,9]. However, this way of allocating turns out to be rather poor in many cases, since the plant is regarded as a black box and the possible causalities are not studied. For instance, in the analysed plant the environmental burdens caused by the combustion in the HRB would also affect the electrical power supplied by the GT, even though no actual functional relationship exists between them except for the steam injected into the combustion chamber.

The International Organisation for Standardization (ISO) recommends that if functional causation can be established, then it must prevail over any other criterion [10]. This principle is also supported in Refs. [7,11], and is applied to a certain extent to cogeneration plants in the ETH's inventory of energy systems [6] and in Ref. [12]. Yet the disaggregation of the equipment that is necessary for the analysis of functional causation within the plant is made in a rather deficient manner in both cases, since only the units whose function is exclusively associated with one of the plant's products are separated and no systematic methodology is proposed.

The fifth of the principles outlined by Finnveden [7] is actually the avoidance of allocation by broadening the system boundaries. For instance, in a cogeneration plant producing steam and power, an alternative means of generating steam should be defined, as well as its corresponding life cycle, and then the calculated loads should be subtracted from those corresponding to the cogeneration plant's inventory. The remaining loads would be associated with the power generation and could be compared with other power plants. On the contrary, if the purpose of the cogeneration plant is considered to be the production of the thermal energy required by the processes, and the generated electricity is regarded as a by-product, an alternative means of power generation should be defined and the associated loads subtracted from those of the cogeneration plant. The result would be the loads associated to the thermal energy. This approach poses the major problem as to what alternative process must be selected, and its application will be discussed later.

4. Allocation based on the exergetic cost

Allocation based on the exergy of the products takes into account their energetic quality, but, since the plant is considered as a black box, the formation process of those flows and the places where irreversibilities are produced are not taken into account. In order to illustrate this shortcoming, one could consider a cogeneration plant with a GT and a heat recovery steam generator. If the steam generator has a very poor efficiency, the product that should be penalised for this inefficiency is the steam, but as the allocation is accomplished in a single step, the electricity generated by the GT will also be penalised to the same extent by irreversibilities it is not directly responsible for.

The main objective of thermoeconomics is the allocation of costs between the products of an energy conversion plant. Thermoeconomics is based on the second law and analyses the cost formation process within plants, for which plants are broken up into a number of subsystems and a number of streams are identified. The theory of the exergetic cost, introduced among others by Lozano and Valero, unifies concepts in a systematic methodology and has the aim (in the first development) of distributing the energy consumed in a process between the products, for which several postulates are established [13]. Since the objective of cogeneration plants is energy conversion, exergetic cost is a more suitable parameter than exergy itself for the allocation of environmental loads, because the origin of the irreversibilities is taken into account.

An allocation procedure supported by many authors, which corresponds to the third point in Finnveden's list and is recommended by ISO when no identifiable causation exists [10], is the distribution of environmental loads according to the economic value of the products. This allocation principle, which is based on the fact that economic value is the actual motor in every process, has some objections such as price variability, and in the case of cogeneration plants, the absence of market value for thermal energy. The goal of thermoeconomics is in fact the economic valuation of energy conversion plant's flows. In the exergetic cost theory, the postulates are finally used to work out the monetary costs of the output flows (exergoeconomic costs), allocating not the exergies of the input flows, but the economic costs of these flows and the equipment. Therefore, in cogeneration plants, the economic allocation would be based on postulates similar to those of the exergetic cost principle.

In spite of all this, allocation based on exergetic costs has some drawbacks as well. Once the exergetic costs of the products have been calculated, the allocation of the environmental loads quantified during life cycle inventory is accomplished in a single step. Nevertheless, if the plant described above is considered, the emission of pollutants per exergy unit of natural gas burnt in the GT's combustion chamber is quite different from that in the post-combustion burner, and the problem would be even worse if the fuels were different. The proposed method does not separate these emissions, whereas the justice principle that must rule every allocation implies that the steam generated in the HRB should be less penalised due to the lower emissions associated with the combustion in the boiler. Bearing in mind all these factors, exergetic cost can be regarded as the most accurate parameter as long as there is only one fuel input, and provided that loads associated with the plant manufacturing and building are negligible as compared with those associated with the fuel, but it fails when several inputs have different associated environmental vectors, as in the reported case-study.

In order to finally solve the problem, a methodology very similar to the calculation of exergoeconomic costs [13] is proposed, but instead of introducing monetary costs in the balance of each subsystem, it is environmental vectors that are incorporated. So environmental burdens associated with the energy flows entering the plant are introduced into their corresponding subsystem and they only affect the products that have a functional relationship to them. Given its similarity to the calculation of exergoeconomic costs, the authors have called this approach 'the method of the exergoenvironmental costs'.

5. Method of the exergoenvironmental costs

An environmental vector or ecovector ($\vec{v}$) is the set of environmental burdens identified in a life cycle inventory. An ecovector can be associated with an input flow or with the life cycle of an equipment unit. When calculating the exergoeconomic costs, all expenditures arising during plant operation and those corresponding to equipment depreciation must be assigned to the useful products. In contrast, when calculating exergoenvironmental costs, it is the ecovectors associated with energy or mass input flows that must be fully allocated to the useful products.

Following the theory developed by Lozano and Valero, the plant must be divided into subsystems, which are linked to each other by energy flows. The definition of the subsystems has to be based on functional criteria, and the number of these subsystems must be enough to adequately describe the plant but not to such an extent that calculations become too complicated. Table 3 contains the nine subsystems defined for the plant described above and Table 4 the 24 energy flows, from which six are useful products. The number of the flows and subsystems correspond to those in Fig. 2. Table 4 also displays energy, exergy (B) and exergetic cost (B^*) values, as well as the exergetic cost per exergy unit. Exergetic costs were calculated through a method analogous to that described below for the calculation of exergoenvironmental costs, but substituting ecovectors for exergy values. It has already been pointed out that the black liquor boiler and the steam generated in it have been excluded from the analysis.

Following the work by Tsatsaronis [14], flows are classified into fuels, products and losses according to their function in each unit. One flow can be a product in one subsystem and fuel in another one. This functional definition of the flows is of the utmost importance for the application of the methodology, and is based on the analysis of energy conversion in each subsystem. Fuels and products may comprise various flows. For instance, in a heat exchanger, the hot stream is a multiple fuel flow with an input and an output, and the cold stream is a multiple product flow.

Flow 5 corresponds to the HRB's exhaust gases. According to the exergetic cost theory, the cost assigned to this stream, since it is a loss, is zero. However, if the propositions are applied just as they are stated in Ref. [13], the whole exergy loss resulting from the release of hot gases to the atmosphere would fall on the cost of the products of the last unit making use of the energy of these gases, that is to say the HRB, whereas the GT's products would not bear this loss at all. As this does not seem fair in the least, an approach very similar to that suggested by Bejan et al. [15] is followed. In the quoted reference, costs are assigned to these loss flows as if they were useful products, and then these costs are distributed between the useful products of the overall plant proportional to their exergy. Here, costs are also assigned to these losses, but at the same time they are introduced in the balance equations as fuels in the components that are responsible for those losses, and this is done proportional to the exergy of the responsible input flows.

Table 3
Defined subsystems

1	Gas turbine
2	Heat recovery boiler
3	Three ways valve I
4	Mix valve I
5	Steam turbine
6	Heat exchanger
7	Three ways valve II
8	Mix valve II
9	Three ways valve III

Table 4
Energy, exergy and exergetic cost of the defined flows

Flows		E (kW)	B (kW)	B^* (kW)	B^*/B
1	Natural gas to GT	32,399[a]	33,654	33,654	1
2	Electrical power supplied by the GT	10,206	10,206	19,970	1.957
3	GT exhaust gases	21,265[b]	9284	18,167	1.957
4	Natural gas to post-combustion burner	11,049[a]	11,477	11,477	1
5	Exhaust gases to air	7112[b]	2437	3479	1.428
6	Feed water to high pressure circuit	2929	255	899	3.531
7	High-pressure steam	21,793	7941	24,537	3.090
8	Feed water to low pressure circuit	493	43	151	3.531
9	Low-pressure steam	3162	799	2476	3.100
10	Feed water to superheated water circuit	4741	215	662	3.075
11	Superheated water	6820	569	1749	3.075
12	Throttled steam	1677	584	1888	3.232
13	Make-up water for injection	5	0	0	
14	Injection steam to GT	1681	560	1888	3.369
15	Steam to ST	20,115	7330	22,649	3.090
16	Electrical power supplied by the ST	1674	1674	5781	3.452
17	Steam extracted from ST	12,968	4068	12,570	3.090
18	ST back-pressure steam	5473	1391	4299	3.090
19	Condensate	2698	252	780	3.091
20	Make-up water	825	0	0	
21	Preheated make-up water	2904	193	1087	5.636
22	Preheated water to HRB feeding	724	48	271	5.636
23	Feed water to HRB	3422	298	1051	3.531
24	Preheated water to process	2180	145	816	5.636

[a] LHV.
[b] Condensation heat not included.

As no loss flow is accounted as far as calculations are concerned, the functional definition of the flows in each subsystem would be as shown in Table 5. The fact that flow 5 appears in the HRB as a product and part of it also as a fuel, is just a mathematical approach that accounts for the proportional distribution of the stack losses between the two components that are responsible for it, namely the HRB and the GT. Hence, part of this loss is also regarded as a fuel in the GT.

Useful products are flows 2, 9, 16, 17, 18 and 24. Not all the energy available in the flows 9, 17 and 18 is used, but part of it goes back to the system as condensate (flow 19), and therefore the proportional part of the flow 19 must be subtracted from these flows to work out the real useful flows. Twenty-four equations are needed to calculate either exergetic or exergoenvironmental costs. Equations corresponding to the exergoenvironmental costs (or ecovectors) are shown in this report, whereas those corresponding to the exergetic costs would be identical by replacing

Table 5
Functional definition of the flows (flows in brackets are multiple flows)

Subsystem	Fuels	Products
Gas turbine	1, 14, 5 (part)[a]	2, 3
Heat recovery boiler	3, 4, 5 (part)[a]	(7–6), (9–8), (11–10), 5
Three ways valve I	7	12, 15
Mix valve I	12, 13	14
Steam turbine	(15–17–18)	16
Heat exchanger	(11–10)	(21-20)
Three ways valve II	21	22, 24
Mix valve II	19, 22	23
Three ways valve III	23	6, 8

[a] The consideration of flow 5 as a fuel is a mathematical approach for the allocation of this loss.

ecovectors by exergetic costs. The 24 equations are extracted from the application of the postulates of Lozano and Valero, taking into account the modification concerning loss flows. The propositions do not follow the order established in Ref. [13].

Proposition 1. *The exergoenvironmental cost is a conservative property.*

Application of this proposition gives rise to nine equations, one for each subsystem the plant has been divided into. This proposition simply means that every input environmental load is assigned to the products.

$$1.\ \vec{v}_1 + \vec{v}_{14} + \vec{v}_5 \frac{\boldsymbol{B}_1}{\boldsymbol{B}_1 + \boldsymbol{B}_4} = \vec{v}_2 + \vec{v}_3 \tag{1}$$

$$2.\ \vec{v}_3 + \vec{v}_4 + \vec{v}_5 \frac{\boldsymbol{B}_4}{\boldsymbol{B}_1 + \boldsymbol{B}_4} = (\vec{v}_7 - \vec{v}_6) + (\vec{v}_9 - \vec{v}_8) + (\vec{v}_{11} - \vec{v}_{10}) + \vec{v}_5 \tag{2}$$

$$3.\ \vec{v}_7 = \vec{v}_{12} + \vec{v}_{15} \tag{3}$$

$$4.\ \vec{v}_{12} + \vec{v}_{13} = \vec{v}_{14} \tag{4}$$

$$5.\ (\vec{v}_{15} - \vec{v}_{17} - \vec{v}_{18}) = \vec{v}_{16} \tag{5}$$

$$6.\ (\vec{v}_{11} - \vec{v}_{10}) = (\vec{v}_{21} - \vec{v}_{20}) \tag{6}$$

$$7.\ \vec{v}_{21} = \vec{v}_{22} + \vec{v}_{24} \tag{7}$$

$$8.\ \vec{v}_{19} + \vec{v}_{22} = \vec{v}_{23} \tag{8}$$

$$9.\ \vec{v}_{23} = \vec{v}_6 + \vec{v}_8 \tag{9}$$

As mentioned before, flow 5 (exhaust gases) is not regarded as a loss when operating, but its ecovector (v_5) is calculated and then proportionally distributed between the flows responsible for it, which are the fuel inputs 1 and 4. This way of operating modifies the values of the intermediate flows, but not the values corresponding to the plant's final products.

The addition of these nine equations results in the overall balance of the plant:

$$\vec{v}_1 + \vec{v}_4 + \vec{v}_{13} + \vec{v}_{20} = \vec{v}_2 + \vec{v}_{16} + \vec{v}_9 + \vec{v}_{17} + \vec{v}_{18} + \vec{v}_{24} - \vec{v}_{19} \tag{10}$$

The environmental burdens associated with the input flows (1, 4, 13 and 20) are thus allocated to the useful flows (2, 16, 9, 17, 18 and 24). The condensate (19) is not an external input to the energy system and, therefore, its calculated environmental vector must be subtracted from the flows that give rise to it (9, 17 and 18) proportional to their exergy, as mentioned before. For example, the real environmental vector associated with the useful product 9 should be finally corrected as follows:

$$\vec{v}_{9,\mathrm{real}} = \vec{v}_9 - \vec{v}_{19}\frac{\boldsymbol{B}_9}{\boldsymbol{B}_9 + \boldsymbol{B}_{17} + \boldsymbol{B}_{18}} \tag{11}$$

Likewise, the real useful energy of this flow would be:

$$E_{9,\mathrm{real}} = E_9 - E_{19}\frac{\boldsymbol{E}_9}{\boldsymbol{E}_9 + \boldsymbol{E}_{17} + \boldsymbol{E}_{18}} \tag{12}$$

Proposition 2. *For the components of a multiple fuel flow in a subsystem, the exergoenvironmental cost per exergy unit (unitary cost) of the output flows must be equal to that of the input flows. A multiple fuel flow consists of one or several flows entering a subsystem and leaving it after transferring part of its exergy.*

This proposition means that when a flow transfers part of its exergy in a subsystem, the environmental loads per exergy unit associated with the input stream must be equal to those associated with the output streams. Five equations are drawn from this proposition:

$$10.\ \frac{\vec{v}_5}{\boldsymbol{B}_5} = \frac{\vec{v}_3 + \vec{v}_4}{\boldsymbol{B}_3 + \boldsymbol{B}_4} \tag{13}$$

$$11.\ \frac{\vec{v}_{17}}{\boldsymbol{B}_{17}} = \frac{\vec{v}_{15}}{\boldsymbol{B}_{15}} \tag{14}$$

$$12.\ \frac{\vec{v}_{18}}{\boldsymbol{B}_{18}} = \frac{\vec{v}_{15}}{\boldsymbol{B}_{15}} \tag{15}$$

$$13.\ \frac{\vec{v}_{11}}{\boldsymbol{B}_{11}} = \frac{\vec{v}_{10}}{\boldsymbol{B}_{10}} \tag{16}$$

$$14.\ \frac{\vec{v}_{19}}{\boldsymbol{B}_{19}} = \frac{\vec{v}_9 + \vec{v}_{17} + \vec{v}_{18}}{\boldsymbol{B}_9 + \boldsymbol{B}_{17} + \boldsymbol{B}_{18}} \tag{17}$$

Exhaust gases (5) are considered as the output component of a multiple fuel whose inputs are flows 3 (flue gases from the GT) and 4 (natural gas supplied to the duct burner).

Proposition 3. *If a subsystem has a total product comprising several components, all of them have the same unitary exergoenvironmental cost.*

The reason for this postulate is that even though two or more independent products may be identified in a unique subsystem, their formation process cannot be separated at the regarded aggregation level, and therefore identical valuation, that is to say identical exergoenvironmental costs per exergy unit, must be assigned to all of them. Six equations are derived from the application of this proposition.

$$15.\ \frac{\vec{v}_3}{\boldsymbol{B}_3} = \frac{\vec{v}_2}{\boldsymbol{B}_2} \tag{18}$$

$$16.\ \frac{\vec{v}_9 - \vec{v}_8}{\boldsymbol{B}_9 - \boldsymbol{B}_8} = \frac{\vec{v}_7 - \vec{v}_6}{\boldsymbol{B}_7 - \boldsymbol{B}_6} \tag{19}$$

$$17.\ \frac{\vec{v}_{11} - \vec{v}_{10}}{\boldsymbol{B}_{11} - \boldsymbol{B}_{10}} = \frac{\vec{v}_7 - \vec{v}_6}{\boldsymbol{B}_7 - \boldsymbol{B}_6} \tag{20}$$

$$18.\ \frac{\vec{v}_{15}}{\boldsymbol{B}_{15}} = \frac{\vec{v}_{12}}{\boldsymbol{B}_{12}} \tag{21}$$

$$19.\ \frac{\vec{v}_{24}}{\boldsymbol{B}_{24}} = \frac{\vec{v}_{22}}{\boldsymbol{B}_{22}} \tag{22}$$

$$20.\ \frac{\vec{v}_6}{\boldsymbol{B}_6} = \frac{\vec{v}_8}{\boldsymbol{B}_8} \tag{23}$$

External valuation. The last two propositions of the theory of the exergetic cost deal with the external valuation of loss flows (considered here in a different manner) and flows entering the plant. From the 24 defined flows, four are plant inputs. Flows 13 and 20 are make-up water, and as their associated environmental loads are almost negligible, their ecovectors can be considered as zero. The other external flows are fuel inputs (1 and 4), which have associated burdens produced throughout the pre-combustion process as well as those related to the combustion. The ecovectors of these flows are, therefore, well-known and will be determined once the functional unit has been chosen.

$$21.\ v_{13} = \vec{\mathbf{0}} \tag{24}$$

$$22.\ v_{20} = \vec{\mathbf{0}} \tag{25}$$

$$23.\ \vec{v}_1 = \vec{v}_1 \tag{26}$$

$$24.\ \vec{v}_4 = \vec{v}_4 \tag{27}$$

If, for example, 1 TJ of gas supplied to the GT is taken as functional unit, $\vec{v}_1$ would be the sum of Table 1 (including all the loads not shown in this list), which accounts for the contribution of the pre-combustion process, and the first column of Table 2, which accounts for the combustion, whereas $\vec{v}_4$ would be calculated by adding Table 1 and the second column of Table 2 and multiplying the result by the ratio of gas burnt in the HRB to gas burnt in the GT. The huge number of different emissions considered in the ETH inventory ($>$500) [6] determines the number of elements of these ecovectors.

If ecovectors associated with the life cycle of equipment were included in the balance equations (1)–(9), those ecovectors would be referred to the chosen functional unit as well, just like depreciation costs when dealing with exergoeconomic costs.

So we have a complete system of 24 equations. The application of the propositions of Lozano and Valero (with the introduced modifications) always results in a system of as many equations as defined flows. The unknowns in this system are vectors, but all these vectors are linear combinations, and hence the system is equivalent to another one with scalar unknowns. The system can be expressed as a matrix system:

$$\mathbf{A} \times \mathbf{V} = \mathbf{X} \tag{28}$$

where **A** is a squared matrix whose elements are scalar and contain the information about the system under study, **X** is a scalar column matrix whose dimension is the number of defined flows and contains the information about the external valuation of the flows entering the plant, and **V** is a column matrix whose elements are the unknown vectors, that is to say, the ecovectors of all the flows. The system can be solved through matrix inversion, obtaining all the ecovectors corresponding to the intermediate and useful products $\vec{v}_i$:

$$\mathbf{V} = \mathbf{A}^{-1} \times \mathbf{X} \tag{29}$$

It must be pointed out that the plant has been assumed to operate ever in the same conditions. Otherwise, calculations for each operation mode should be made, and the results should be weighted with regard to the time each mode lasts.

Environmental vectors also include information about natural resources used throughout the life cycle. Knowing the exergy of these resources, the methodology also serves to calculate the exergetic cost of the products. In fact, any information associated with the flows may be added to the vectors, for example the monetary cost, and hence the exergoeconomic costs would be calculated as well. For this extension, the balance equations (Eqs. (1)–(9) in this example) must include the equipment. The obvious reason is that, while the influence of the equipment is usually negligible with regard to environmental burdens, the same is by no means applicable to economic costs, which must include equipment depreciation and maintenance costs. The external environmental costs associated with the environmental burdens may also be calculated, and then this information can be added. The sum of internal and external costs would result in the total social cost of the energy flows.

6. Comparison of the results

As the list of environmental loads resulting from the inventory is very large and difficult to deal with, results from the impact assessment step will be used in order to compare different allocation procedures. The method that has been employed for the impact assessment is the Eco-indicator 95 [16], which is a widely used and accepted methodology. Further developments of the Eco-indicator have been made after the 95 version, incorporating impacts such as radioactivity and resources depletion, but this one was most widespread at the time the analysis was carried out. In this method, as illustrated in Fig. 3, emissions are aggregated within a series of impact categories depending on the sort of environmental problem they contribute to, weighting pollutants against each other by means of a characterisation factor according to their contribution to each impact. For example, in the ‘greenhouse effect’ category, 1 kg of CO_2 is weighted with a factor 1, whereas 1 kg of CH_4 is weighted with a factor 11. The result is a unique value for each impact category. Finally, the severity of each impact is weighted in accordance with a distance-to-target principle in the evaluation step, so that a single score (measured in points) is reached in the end. These points are a measure of the total environmental impact of a product, but have no meaning on their own. They are only meaningful as a comparison of different products or processes, so that if 1 TJ of electricity generated by a certain process results in a lower number of points than another generation system, the former is advantageous from an environmental point of view. There is a certain level of subjectivity in the evaluation phase as the comparison of different environmental problems is not only a scientific problem. This is one of the drawbacks of the LCA methodology that must be overcome to gain widespread acceptance.

The results of the application of the different allocation procedures are displayed in Table 6. In the last two rows the flows have been gathered into electrical power (sum of the power generated by the GT and the ST) and thermal energy (sum of the various steam flows and hot water used in the factory’s process). The results are presented in points per TJ of generated electricity and points per TJ of thermal energy.

Allocation based on energy is very poor, since it does not take energy quality and its real value into account, and for this reason the same environmental loads per energy unit are assigned to power and thermal energy. When the exergy criterion is applied, the indicator value associated

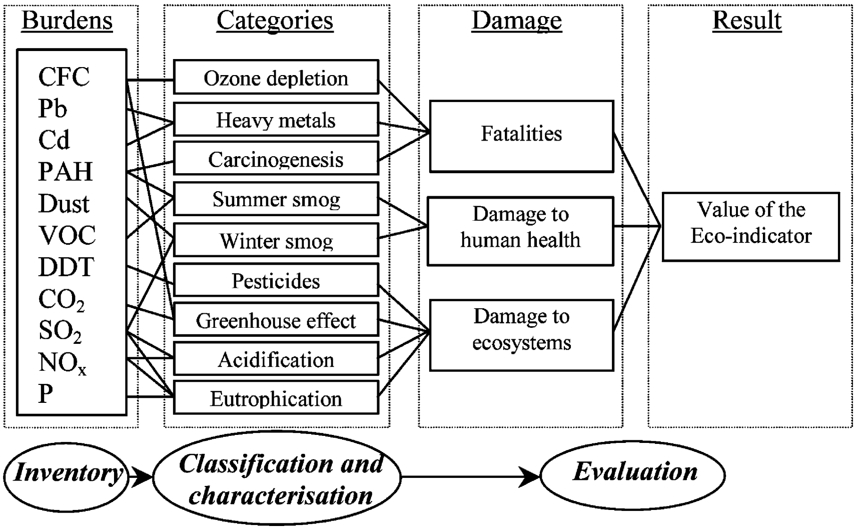

Fig. 3. Layout of the Eco-indicator 95 method of impact analysis.

Table 6
Values of the Eco-indicator 95 according to different allocation criterions. All the results are given in points/TJ

	Energy	Exergy	Exergetic costs	Exergoenvironmental costs
GT power	46.36	84.77	66.27	89.79
ST power	46.36	84.77	116.92	83.98
LP steam	46.36	23.48	29.08	20.89
ST extracted steam	46.36	29.16	36.00	25.86
ST back-pressure steam	46.36	23.63	29.17	20.95
Preheated water	46.36	5.63	12.68	9.11
Electrical power	46.36	84.77	73.41	88.97
Thermal energy	46.36	24.73	31.13	23.26

with electrical power is nearly multiplied by two compared to the energy criterion. Allocation based on exergetic cost differs from that based on exergy by the fact that irreversibilities produced in each equipment unit only affect the energy flows related to that unit, and not the plant as a whole. Thus, the GT's electrical power is not affected by the irreversibilities arising in the HRB, except for the steam injection and for the fact that stack losses are allocated to all the products. This is the reason why environmental loads assigned to electrical power (mostly generated in the GT) are lower when using the exergetic cost as the allocation principle.

Nevertheless, both exergy and exergetic cost allocation methods distribute the overall life cycle loads in a single step, and thus no distinction is made between the combustion in the GT and in the HRB's duct-burner. The problem would become more acute if the black liquor boiler, whose emissions should only affect the steam generated in it, were included in the analysis. The exergoenvironmental loads method overcomes this problem and is the fairest allocation procedure, as well as a systematised methodology. In order to compare in detail the divergent results of the methods of exergetic costs and exergoenvironmental costs, Figs. 4 and 5 depict a comparison of the number of points resulting for each impact category after the evaluation step of the Eco-indicator 95 procedure, both for the aggregated electrical power and thermal energy. The addition

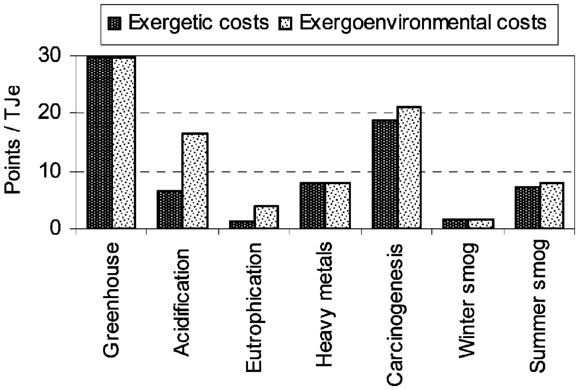

Fig. 4. Comparison of impact categories for electrical power using two different allocation principles.

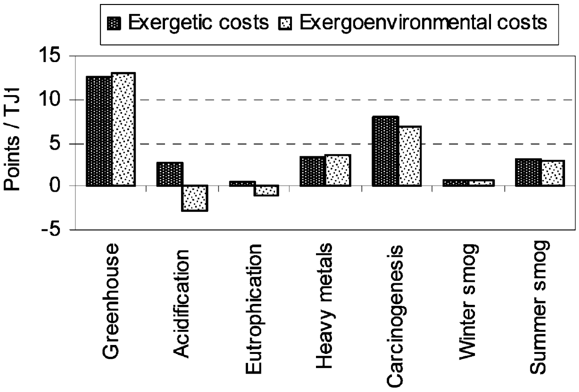

Fig. 5. Comparison of impact categories for thermal energy using two different allocation principles.

of the points of each category results in the total number of points given in Table 6. ‘Ozone layer depletion’ and ‘Pesticides’ are excluded because of their very small value.

If the handling of the entire ecovectors is rather awkward, the aggregation of all the impacts in one single indicator misses much information. An intermediate solution like this, showing the impact categories, can be useful to reveal some interesting aspects, like for example the negative value of the categories ‘Acidification’ and ‘Eutrophication’ for the thermal energy when the exergoenvironmental method is applied, which accounts for the destruction of NO_X in the HRB’s duct burner. This cannot be revealed by the application of other allocation principles. The fact that, when reduced to a single indicator, the result of applying the exergy criterion is similar to that of the exergoenvironmental method, is a sheer matter of chance whose cause lies on the peculiarities of the plant analysed, for these methods differ substantially. This also reveals the dangers of aggregating the data without further assessment.

7. Applicability of the proposed methods

The exergetic costs and exergoenvironmental costs methods are equivalent unless the environmental loads associated with the equipment (manufacture and maintenance) are not negligible or, like in the case studied in this report, there are several energy flows entering the plant with different ecovectors. Another good example of this latter case would be a cogeneration plant in which biomass and a conventional fuel were used. Although the method has been developed for cogeneration plants, its application can be extended to any energy plant in which a number of products (all of them measurable in energy units) are obtained. In such a case, exergy is the variable best reflecting the value of those products, and the analysis of the formation process of the flows is the best means of allocating environmental burdens. Refineries are good examples of plants where the proposed method is applicable as well.

In any case, allocation itself only makes sense when the resulting energy products are used to obtain different market products. If all of them were used in a process yielding a single product, allocation would not be necessary, since this product would finally have associated all the environmental burdens of the cogeneration plant’s life cycle. However, as in most cases at least part of the electrical power is sold to the electrical network, it is necessary to separate loads corresponding to different flows.

The avoidance of allocation by broadening the system boundaries, which was mentioned in Section 3, gives rise to the problem of selecting the alternative process. If, for instance, the alternative power generation system is very pollutant, the result could lead to substantially low environmental burdens (some of which might be even negative) being allocated to the thermal energy and hence to the commercial products of the factory making use of this energy. Since transparency and justice must rule every LCA, this allocation principle must only be used when there is an accepted agreement about the standard alternative processes that must be considered.

The choice of one method over another will depend on the aim of the study. If this is, for example, the comparison between different means of power generation, extension of system boundaries is a very suitable option as long as a proper alternative process for thermal energy generation is selected. On the contrary, if the goal is to make an as exact as possible LCA of the products of a factory where a cogeneration plant is installed, one of the proposed methods should be used, the exergoenvironmental costs being the most appropriate. This method results in a correct allocation and allows for a fair pricing of the products (both the factory commodities and the surplus energy) in case the external costs are considered in the future.

8. Conclusions

Allocation of environmental loads between the useful products of a cogeneration plant, and in general of any energy conversion plant yielding more than one useful product, is an issue that must be addressed within the framework of LCA.

As no direct causation can be established between the different products and environmental loads, we have to resort in principle to allocation based on some parameter representing the products. Exergy is far more suitable than energy and is the most accepted parameter. Nevertheless, this criterion regards plants as black boxes and fails to analyse the formation process of the flows and the origin of the irreversibilities. Thermoeconomics provides a powerful tool for the analysis of the formation process through the second law. Allocation based on exergetic cost of the products is a more accurate way of carrying out the allocation, since each product bears the irreversibilities it is related to. This criterion, however, continues to carry out allocation of the overall life cycle loads in a single step, and thus it is not accurate when there are several inputs with different associated environmental vectors. The ‘exergoenvironmental costs’ procedure, herein introduced and so-called because of its similarity to exergoeconomic costs, overcomes this problem as the different ecovectors are incorporated in the balance in the subsystems in which they come into play.

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